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BEAM-BEAM SIMULATIONS WITH DISPLACED BEAMS FOR PEP-II

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ABSTRACT

In line with past experience, it is likely that smoothness of operation will require PEP-II to inject beams so that their orbits are displaced from each other at the interaction point (IP). In this note we continue an investigation of the pros and cons of horizontal vs. vertical beam displacement for the APIARY 7.5 design from the perspective of the beam-beam interaction. Parasitic collisions (PCs) are included. We conclude that: (1) for the orbit bump to be safe and effective, the magnitude of the displacement must be a few σ_{0x}'s whether the separation is horizontal or vertical; (2) vertical separation is clearly safer than horizontal on account of the potentially adverse effects from the PCs; (3) horizontal separation has the advantage that there is no significant beam blowup in case that the beams are slowly brought back into collision; (4) the design of a horizontal separator bump would likely be complicated by tight constraints imposed by the PCs, whereas a vertical separator bump would not be subject to such constraints.

This revised version also contains results for the new IR design, with $\beta^*_{y,-} = 2$ cm.

1. Introduction.

Present and past e^+-e^- colliders have found it necessary, or at least very useful for the smoothness of the injection process, to inject the beams so that they do not collide during the filling process. This is especially true for colliders that must ramp up in energy after injection. It is reasonable to expect that PEP-II will exhibit a similar requirement, especially because of the high operational reliability demanded from this (or any other) B factory.

In a simplified description, the injection process can be divided up into four stages:

(1) Turn on the closed orbit bump in the empty machine.

(2) Inject the first beam into the empty machine.

(3) Inject the second beam.

(4) Bring the beams into collision by turning off the orbit bump.

Step (3) of this process has been studied by simulations[1] for the first batch of the positron beam, in which the bunch current is 20% of the nominal value. The main purpose of this work was to study the transient effects of the dynamics for the first few damping times, during which time the injected beam orbit damps down to the nominal orbit, and the emittances reach their steady-state values. Both vertical and horizontal injection were studied in this manner. In one of the horizontal-injection cases studied the beams were assumed to be vertically separated at the IP and the PCs.

In this note we continue such a study by focusing on the intermediate stage between steps (3) and (4). That is, we make the assumption that all injection transient effects have died down, both beams have reached full current and the emittances their nominal, steady-state values, but the orbit bump is still turned on. We focus on the pros and cons in a comparison between vertical and horizontal orbit bump.

The issues that arise in this study are, in principle, distinct from the transients that appear during the injection process. Indeed one may have any combination of vertical injection with vertical separation, or horizontal injection with vertical separation, etc. Furthermore, if the beams are slowly brought into collision in step (4) of the injection process, the results presented here also allow a rough understanding of what would happen during this beam-collapsing process. An implicit assumption that is necessary for the relevance of these simulations to the beam-collapsing process is that the time scale of the switching-off of the separators is longer than a few damping times. If the beam-collapsing process is fast (on the order of one damping time or less), our simulations are probably relevant only to the static situation existing before step (4) is taken.

We ran simulations with the code TRS[2] in which the beams were deliberately displaced at the IP and the first PCs, either vertically or horizontally. Thus the beam separation implemented in these simulations can be thought of as arising from a nominally-closed orbit bump that encompasses the IP and the first PCs. The simulations were done at full beam current, and the emittances had their nominal, steady-state, values. PCs beyond the first were not considered, even though the horizontal-separation alternative would almost certainly demand that they be included in a faithful simulation.

The conclusion is that vertical separation is clearly favored over horizontal on account of the diminished potentially adverse effects from the PCs. When the beams are vertically separated, all PCs are weaker than nominal and the dynamics is essentially determined by the main collision at the IP. In this case a vertical separation $d_y \gtrsim (1\text{-}2)\sigma_{0x}$ is probably adequate for smooth injection (note that it is σ_{0x} and not σ_{0y} that determines the scale of the vertical separation). If the beams are separated horizontally, the closed orbit bump that implements this separation must be tightly constrained by the lattice functions and phase advances of the PC locations; there is no such constraint in the vertical-separation case. In the (unlikely) event that the orbit bump could encompass only the IP and the first PCs, a horizontal separation $3 \lesssim d_x/\sigma_{0x} \lesssim 5$ would seem adequate. If d_x/σ_{0x} is $\lesssim 3$, the bump is probably not very effective, and if d_x/σ_{0x} is $\gtrsim 5$ the adverse effects of the PCs can become quite severe. If the horizontal bump must encompass “outer” PCs, as it seems likely it must, care must be exercised in its design so that the beams do not come too close to each other at any PC location in the separated state.

The horizontal-separation alternative does have the advantage that the simulations show no significant beam blowup when the beams are slowly brought into collision. In the vertical-separation case, on the other hand, the simulations show beam blowup of ~100% in the vertical dimension when the beam centers come together by a distance $d_y \sim (1\text{-}2)\sigma_{0y}$. Since PEP-II has conservative beam-stay-clear specifications, this temporary beam blowup seems a small price to pay, if any, for the added safety and simplicity of the vertical separation option. In addition, this blowup would probably not materialize in the event that the orbit-collapse process is fast.

Qualitatively similar conclusions are reached for the new IR design, with $\beta^*_{y,-}= 2$ cm, although the vertical separation alternative shows clearly better behavior than for APIARY 7.5.

2. Assumptions.

The results below are in the form of beam blowup, σ/σ_0, plotted vs. d_x/σ_{0x} or d_y/σ_{0y} for horizontal or vertical separation, respectively. Here σ_{0x} and σ_{0y} are the nominal, steady-state, rms beam sizes at the IP, and d_x or d_y is the orbit separation at the IP in either case. In the horizontal separation case we varied d_x while keeping d_y fixed, and conversely for the vertical case.

We also assumed that the beam separation is implemented by a closed orbit bump that is symmetric about the IP and whose kicking elements (*e.g.*, orbit deflector magnets) are outside the region encompassing the IP and the PCs (however, see Sec. 4 below). Since in APIARY 7.5 there are no focusing elements between the IP and the first PC, the closed orbits inside this region are parallel-displaced from the nominal orbits. As a result, the orbit separation at each PC is related to that at the IP by simple geometry as follows:

$$\text{Horizontal separation case:}\quad \begin{cases} d_{IP} = d_x & (d_y = 0 = \text{fixed}) \\ d_{PC1} = d_0 + d_x & (d_y = 0 = \text{fixed}) \\ d_{PC2} = d_0 - d_x & (d_y = 0 = \text{fixed}) \end{cases} \tag{1}$$

$$\text{Vertical separation case:}\quad \begin{cases} d_{IP} = d_y & (d_x = 0 = \text{fixed}) \\ d_{PC1} = d_y & (d_x = d_0 = \text{fixed}) \\ d_{PC2} = d_y & (d_x = d_0 = \text{fixed}) \end{cases} \tag{2}$$

where d_0 is the nominal orbit separation at the PCs (d_0 = 3.498 mm for either IR design).

Except for d_x and d_y, all parameters in these simulations had nominal values corresponding to the IR designs consideed, listed in Tables 1 and 2 below. The simulation was run for 5 damping times in all cases, with 256 superparticles per bunch. Thick-lens effects of the beam-beam collision were represented by 5 slices. The working point was (0.64, 0.57) for both beams.

3. Results.

3.1 Horizontal separation case

As implied by in Eq. (1), when the orbits are displaced horizontally, one of the parasitic collisions (called PC2) gets stronger, while the other one (PC1) gets weaker. The collision at the IP also gets weaker. As one can see in Fig. 1 below, beam blowup is not significant provided the separation at the IP is such that $d_x/\sigma_{0x} \lesssim 5$–10. In this regime the PCs are still well separated (for an IP separation $d_x/\sigma_{0x} = 5$, the PC separations are $d_{PC2}/\sigma_{0x,+}= 7.1$ and $d_{PC1}/\sigma_{0x,+}= 12.2$; the nominal head-on case has $d_x= 0$ and $d_{PC2}/\sigma_{0x,+}= d_{PC1}/\sigma_{0x,+}= 9.64$).

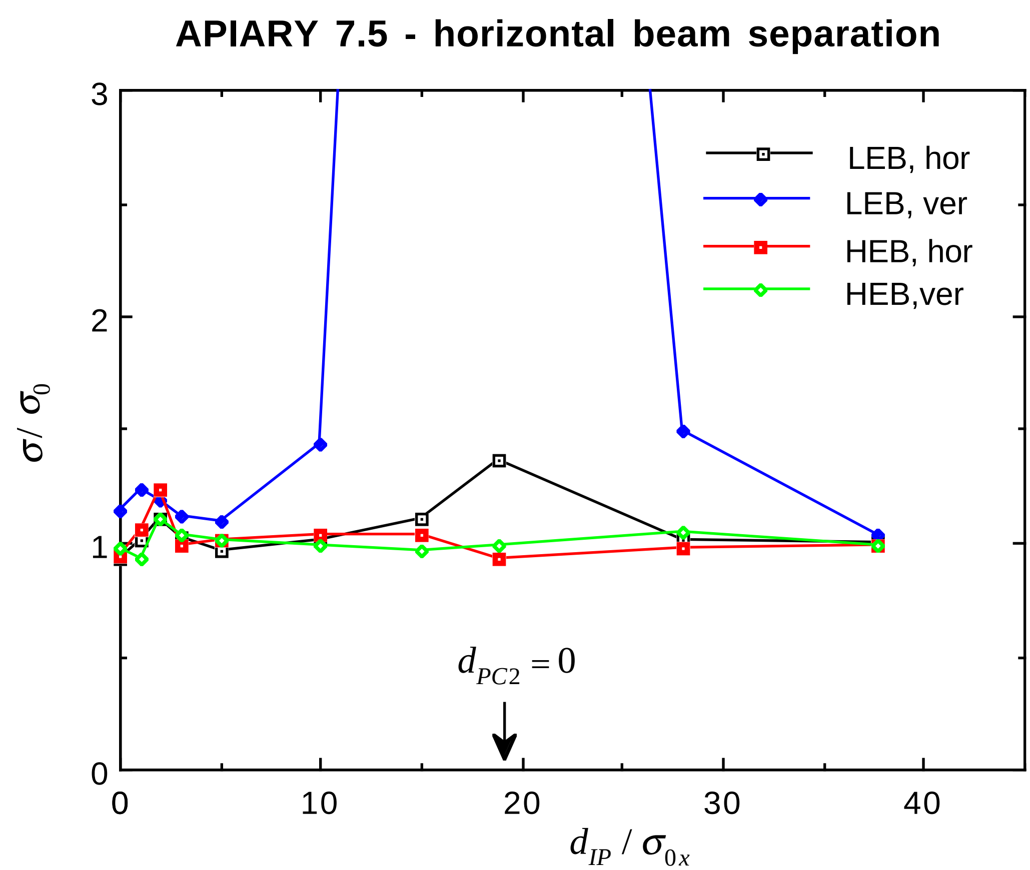

Fig. 1: Beam blowup as a function of horizontal beam separation at the IP. As the beam separation at the IP increases, the separation at one of the PCs (called PC1) increases, while the separation at the other (PC2) decreases. The arrow indicates the separation at which there is a head-on collision at PC2.

However, as one might expect, when the IP separation is so large that the beams collide head-on at the PC2 location (indicated by the arrow labeled "d_{PC2}=0" in the plot), the beam blowup is very large and the simulations also show particle loss. As the beams are further separated, they eventually become so far apart that there are effectively no beam-beam collisions. Thus the last point in the plot, at the unrealistically large separation d_x/σ_{0x} = 37.7, is such that $d_{PC2}/\sigma_{0x,+}$= 9.6 and $d_{PC1}/\sigma_{0x,+}$= 28.9, and one sees that, indeed, there is no beam blowup.

3.1 Vertical separation case

In this case, as implied by in Eq. (2), the beams are always more separated than nominal. The results are shown in Fig. 2. The LEB blowup becomes substantial (~100%) when $d_y/\sigma_{0y} \gtrsim 1$, and it does not come back down to nominal (*i.e.*, unity) until the separation is $d_y/\sigma_{0y} \gtrsim 25$, corresponding to $d_y \gtrsim \sigma_{0x}$, except for a temporary decrease. This behavior seems to be a natural consequence of the scales that enter the Bassetti-Erskine formula for the electric field $\boldsymbol{E}$ of an elliptical gaussian charge distribution. Indeed, for $\sigma_{0y} \ll \sigma_{0x}$, the horizontal electric field $E_x(x,y,\sigma_{0x},\sigma_{0y})$ rises and falls off in x with a scale set by σ_{0x} . However, the vertical field $E_y(x,y,\sigma_{0x},\sigma_{0y})$ rises in y with a scale set by σ_{0y} , but falls off, also in y, with a scale set by σ_{0x} and *not* by σ_{0y}.

In Fig. 2 the vertical beam blowup of the LEB does not fall smoothly as the separation is increased beyond $d_y \gtrsim \sigma_{0y}$. We conjecture that this behavior is almost certainly due to resonances crossed by the beam core as the effective working point moves due to the d_y-dependence of the beam-beam tune shift. Once the cores of the two beams are well separated, the long-range beam-beam interaction introduces a tune shift but not much of a tune spread. Thus it should be possible to compensate this tune shift by an appropriate shift in the working point such that the beam core remains at the same place in the tune plane. We did not do this in the simulations: the lattice tunes were held fixed at (0.64, 0.57) for all values of the separation. If our conjecture is correct, the beam blowup in the vertical separation case could be made to behave more smoothly and be brought down to nominal values for much smaller separations than those implied by the results in Fig. 2. However, tuning the machine seems impractical during the actual beam-collapsing process, so that this possibility for smoother behavior seems to be of academic interest only.

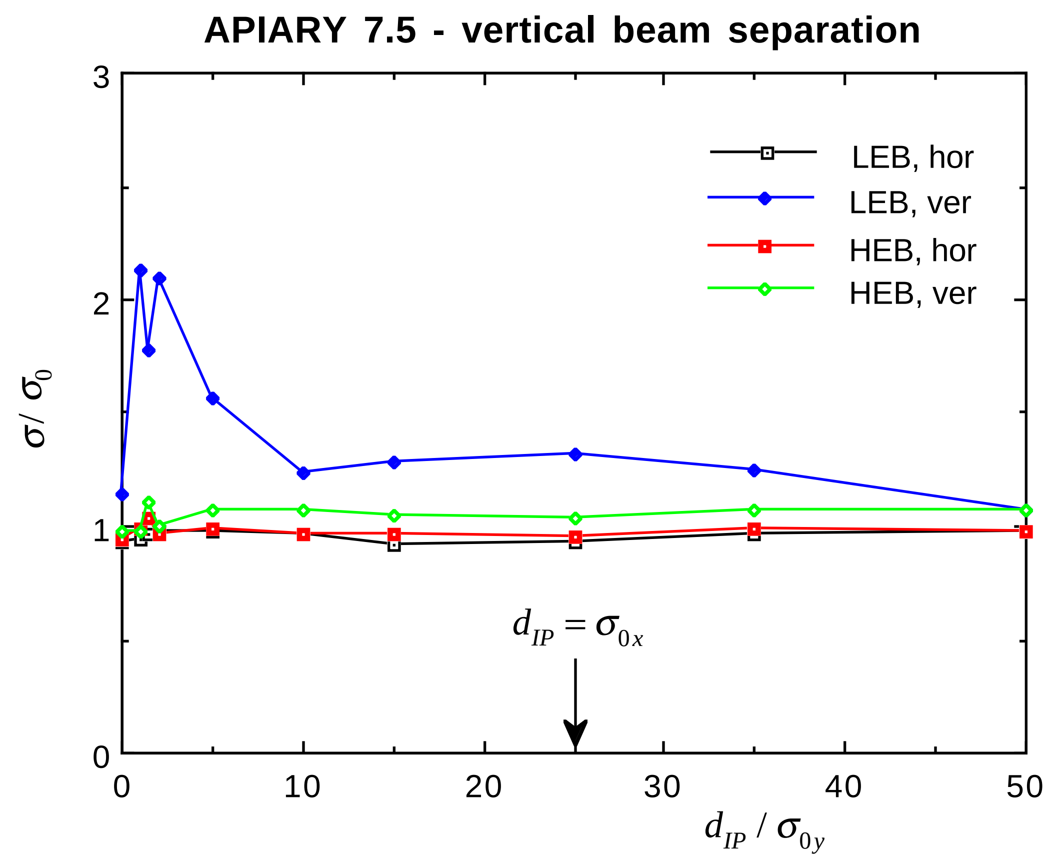

Fig. 2: Beam blowup as a function of vertical beam separation. As the beam separation at the IP increases, so does the separation at both PCs. The arrow indicates the point at which the vertical separation equals the nominal horizontal beam size.

4. Results for the new IR design with $\beta^*_{x,-}/\beta^*_{y,-}$ = 50/2 cm.

A new IR design, with $\beta^*_{x,-}/\beta^*_{y,-}$ = 50/2 cm, is being considered for PEP-II. In this design the bunch currents and emittances have new values such that the beam-beam parameters and nominal luminosity retain the same values as in APIARY 7.5. Table 2 contains a full list of parameters for this new design.

Figures 3 and 4 show the results for the new design, for horizontal and vertical separation, respectively. The results for horizontal case are qualitatively similar to those for APIARY 7.5. The vertical case, however, shows improved performance (lesser and smoother blowup); this is probably due to the weaker effects of the PCs in the new design.

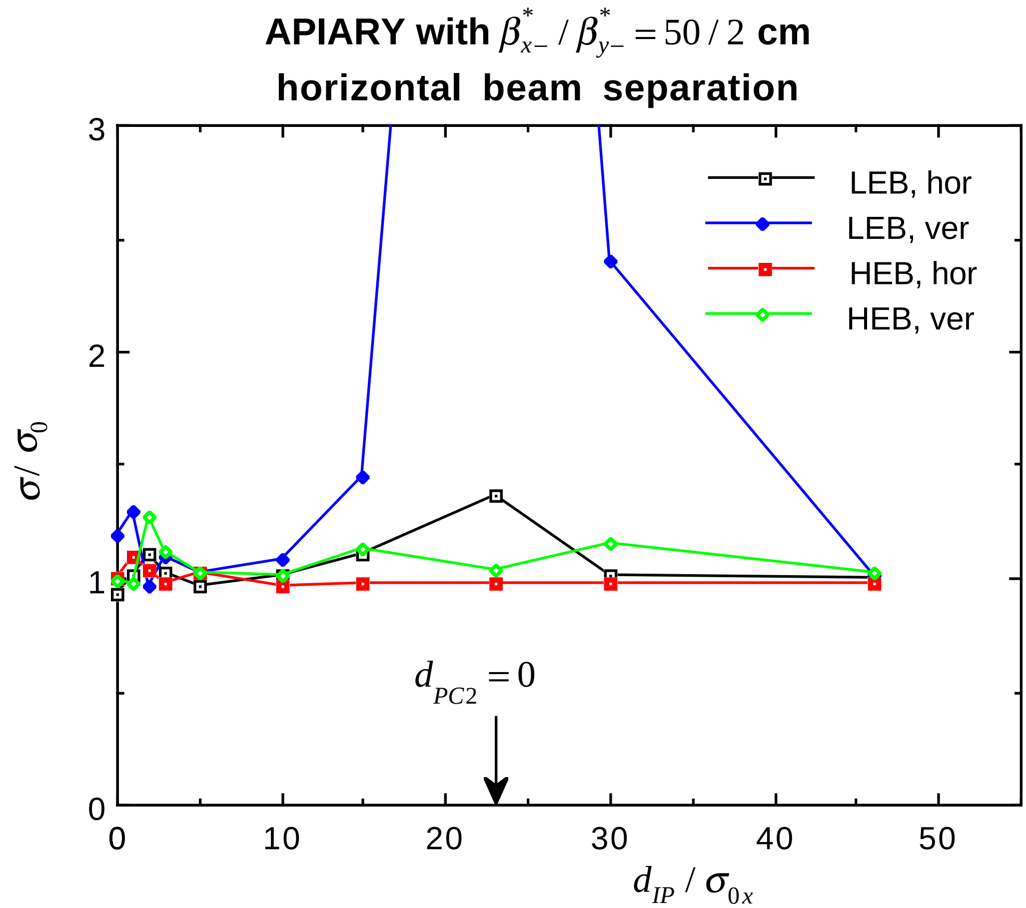

Fig. 3: Beam blowup for the new IR design as a function of horizontal beam separation at the IP. As the beam separation at the IP increases, the separation at one of the PCs (called PC1) increases, while the separation at the other (PC2) decreases. The arrow indicates the separation at which there is a head-on collision at PC2.

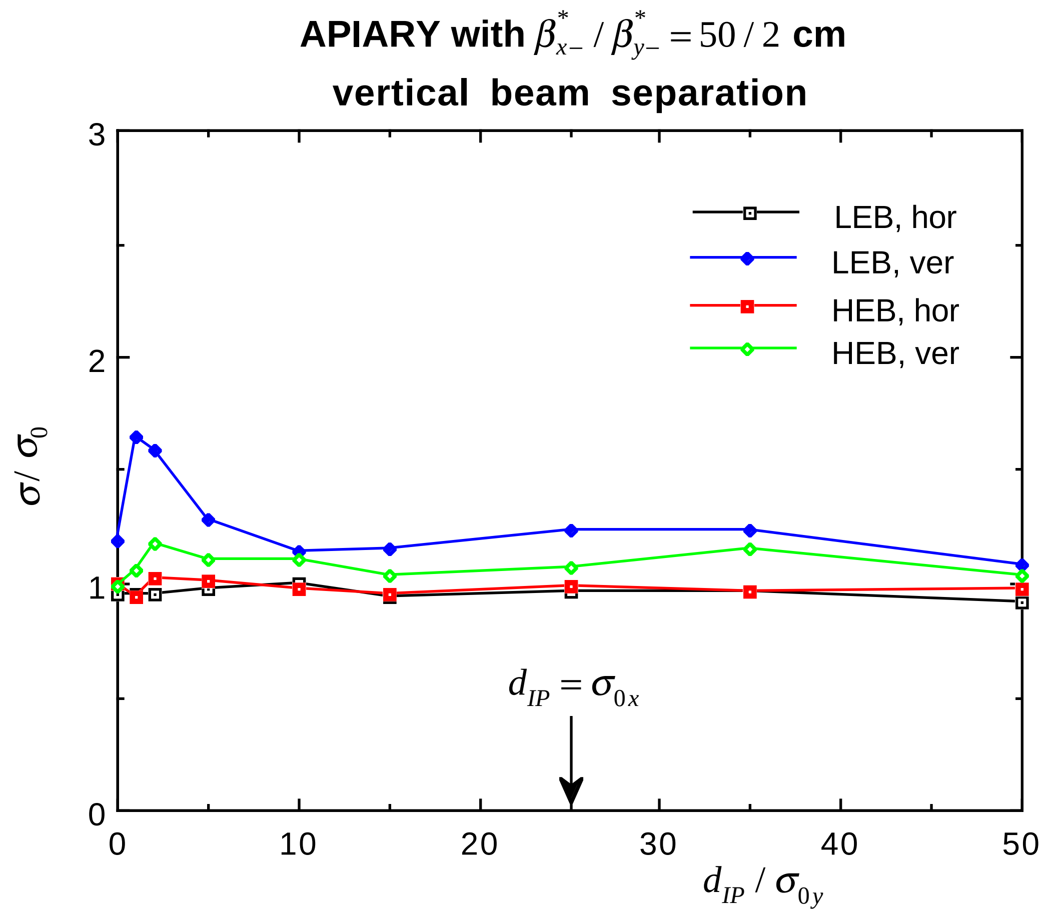

Fig. 4: Beam blowup for the new IR design as a function of vertical beam separation. As the beam separation at the IP increases, so does the separation at both PCs. The arrow indicates the point at which the vertical separation equals the nominal horizontal beam size.

5. Basic constraints for a closed-orbit bump.

The simplest closed-orbit bump is implemented by means of two kicking elements (electrostatic separators, or magnetic orbit deflectors) separated by a distance such that the intervening phase advance is

$$\Delta\nu = 1/2,\ 3/2,\ 5/2,\ \cdots \tag{3}$$

Lattice designs under current consideration[3] show that even the first option, $\Delta\nu$=1/2, implies that the kicking elements must be located at a distance greater than 2.5 m from the IP. This implies that *all four* PCs on either side of the IP would be encompassed by the orbit bump. This happens to be true for both rings, whether the separation is vertical or horizontal, and for both IR designs (APIARY 7.5 and the new design with $\beta^*_{x,-}/\beta^*_{y,-}$=50/2 cm). Of course, it is in principle possible to separate beams by means of a more elaborate orbit bump (*e.g.*, with more than two kicking elements), or a bump that is not closed (*i.e.*, the orbit distortion propagates throughout the entire ring). Either alternative entails complications that are not evaluated here.

6. Conclusions.

As a practical matter, we conclude that it is σ_{0x} that determines the scale for the falloff of the beam blowup whether the separation is horizontal or vertical. In the vertical separation case, the naïve expectation that the scale for the falloff should be determined by σ_{0y} is incorrect. This implies that, if the beams need to be separated during injection, this separation must be several σ_{0x}'s in magnitude whether it is vertical or horizontal, for it to be effective. This conclusion is consistent with PEP[1] and CESR[4] experience. We conjecture, however, that, in the vertical-separation case, the beam blowup could be made significantly closer to nominal for $d_y < \sigma_{0x}$ by appropriate tuning. This is, in fact, what has been observed[5] in a controlled beam-separation experiment at VEPP-4. However, this possibility seems impractical during the injection process.

If the beams are separated horizontally during injection, and if the orbit bump could encompass only the IP and first PCs on either side of the IP, the simulations imply that an IP separation $\sim 3\sigma_{0x}$ would be adequate. However, if the separation is more than $\sim 5\sigma_{0x}$, there is a good chance for severe adverse effects from the PCs closest to the IP. Furthermore, if the closed orbit bump that effects the beam separation is not confined to the region encompassing the IP and the first PCs, there is no guarantee that there would not be a near head-on collision at some "outer" PC, also with severe adverse effects. Once the exact location of the orbit bump magnets is decided upon, one can compute the distorted closed orbit at all PC locations encompassed by the bump and one can determine whether its design is safe or not. In practice, of course, this means that the design of the bump is constrained by the location, lattice functions and phase advances of the PCs. Even if an orbit bump encompassing only the IP and first PCs were possible, the nature of the approximations involved in the present calculations would make it risky and premature to adopt a design for an orbit bump with an operating amplitude $3 \lesssim d_x/\sigma_{0x} \lesssim 5$.

If the beams are separated vertically, *all* PCs encompassed by the closed orbit bump are weaker than nominal in the displaced state and thus negligible; the beam dynamics is essentially determined by the main collision at the IP. Thus there should be no serious concerns from the effects of the PCs during the injection process, and hence no constraints thereof on the design of the orbit bump. In this vertical-separation case an orbit displacement $d_y \gtrsim (1\text{-}2)\sigma_{0x}$ (*not* σ_{0y}) would seem to be adequate.

If the beams are slowly brought into collision from their separated state, there is no significant blowup in the horizontal-separation case. This is an advantage over the vertical-separation case, in which the LEB undergoes a vertical blowup of ~100% when the beam centers come together within a distance $d_y \sim (1\text{-}2)\sigma_{0y}$. Since PEP-II has a comfortable beam-stay-clear specification, this temporary beam blowup seems a small price to pay, if any, for the added comfort of decoupling the beam separation mechanism during injection from the potentially adverse effects of the PCs. In addition, this blowup would probably not materialize in the event that the orbit-collapsing process is fast.

The new design, with $\beta^*_{x,-}/\beta^*_{y,-}$=50/2 cm, shows qualitatively similar behavior in the horizontal separation case as does APIARY 7.5. The vertical separation alternative, however, is clearly better (lesser and smoother blowup). This improved behavior is almost certainly a consequence of the weaker strength of the PCs in this design.

Thus there seems to be no question, from the beam-beam perspective, that vertical beam separation during injection is cleaner and more conservative than horizontal separation, at least for the two APIARY designs studied here.

7. Acknowledgments.

We are grateful to Tong Chen and Sasha Zholents for useful discussions and to NERSC for supercomputer support.

8. References.

1. Y.-H. Chin, "Beam-Beam Dynamics During the Injection Process at the SLAC/LBL/LLNL B-Factory," ABC-51/LBL-31434/ESG-158; see also *PEP-II: An Asymmetric B Factory Design Update*, February 1992, Sec. 4.4.5.

2. J. L. Tennyson, undocumented code "TRS," 1989.

3. D. Robin, private communication.

4. M. Billing, private communication.

5. A. Zholents, private communication.

Table 1

APIARY 7.5 PRIMARY PARAMETERS
Nominal case; $\mathcal{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2199.32	2199.32
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	9.5	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.5×10^{-3}	2.41×10^{-3}
ν_s	0.05	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	3.878×10^{10}
I [A]	2.147	1.479
ε_{0x} [nm-rad]	91.90	45.95
ε_{0y} [nm-rad]	3.676	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.426	7.426
τ_x [turns]	5,014	5,014
τ_y [turns]	5,014	5,014

Table 1 (contd.)

APIARY 7.5 IP AND PC PARAMETERS
Nominal case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)		HER (e^-)	
Δs [cm] [a)]	62.9816			
d [mm] [a)]	3.498			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$ [a)]	0	0.1645	0	0.1112
$\Delta\nu_y$ [a)]	0	0.2462	0	0.2424
β_x [m]	0.375	1.433	0.750	1.279
β_y [m]	0.015	26.46	0.030	13.25
α_x	0	–1.680	0	–0.840
α_y	0	–41.988	0	–20.994
σ_{0x} [μm]	185.6	362.9	185.6	242.4
σ_{0y} [μm]	7.426	311.9	7.426	156.1
$\sigma_{0x'}$ [mrad]	0.495	0.495	0.248	0.248
$\sigma_{0y'}$ [mrad]	0.495	0.495	0.248	0.248
d/σ_{0x}	0	9.639	0	14.429
ξ_{0x}	0.03	–0.000336	0.03	–0.000150
ξ_{0y}	0.03	+0.006200	0.03	+0.001553
$\xi_{0x,tot}$ [b)]	0.0293		0.0297	
$\xi_{0y,tot}$ [b)]	0.0424		0.0331	

[a)] The first PC occurs at a distance Δs and at a phase advance $\Delta\nu$ from the IP. At this point the nominal orbits are separated horizontally by a distance d.

[b)] The total nominal beam-beam parameter is defined to be $\xi_{0,tot} \equiv \xi_0^{(\mathrm{IP})} + 2\xi_0^{(\mathrm{PC})}$.

Table 2

APIARY ($\beta^*_{y,-}$=2 cm design) PRIMARY PARAMETERS
Nominal case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)	HER (e^-)
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2199.32	2199.32
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	9.5	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.5×10^{-3}	2.41×10^{-3}
ν_s	0.05	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	2.586×10^{10}
I [A]	2.147	0.986
ε_{0x} [nm-rad]	61.27	45.95
ε_{0y} [nm-rad]	2.451	1.838
β^*_x [m]	0.375	0.500
β^*_y [m]	0.015	0.020
σ^*_{0x} [μm]	151.6	151.6
σ^*_{0y} [μm]	6.063	6.063
τ_x [turns]	5,014	5,014
τ_y [turns]	5,014	5,014

Table 2 (contd.)

APIARY ($\beta^*_{y,-}$=2 cm design) IP AND PC PARAMETERS
Nominal case; $\mathcal{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)		HER (e^-)	
Δs [cm] [a]	62.9816			
d [mm] [a]	3.498			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$ [a]	0	0.1645	0	0.1432
$\Delta\nu_y$ [a]	0	0.2462	0	0.2449
β_x [m]	0.375	1.433	0.500	1.293
β_y [m]	0.015	26.46	0.020	19.853
α_x	0	–1.680	0	–1.260
α_y	0	–41.988	0	–31.491
σ_{0x} [μm]	151.6	296.3	151.6	243.8
σ_{0y} [μm]	6.063	254.6	6.063	191.0
$\sigma_{0x'}$ [mrad]	0.404	0.404	0.303	0.303
$\sigma_{0y'}$ [mrad]	0.404	0.404	0.303	0.303
d/σ_{0x}	0	11.81	0	14.35
ξ_{0x}	0.03	–0.000224	0.03	–0.000152
ξ_{0y}	0.03	+0.004133	0.03	+0.002326
$\xi_{0x,tot}$ [b]	0.0296		0.0347	
$\xi_{0y,tot}$ [b]	0.0383		0.0278	

[a] The first PC occurs at a distance Δs and at a phase advance $\Delta\nu$ from the IP. At this point the nominal orbits are separated horizontally by a distance *d.*

[b] The total nominal beam-beam parameter is defined to be $\xi_{0,tot} \equiv \xi_0^{(IP)} + 2\xi_0^{(PC)}$.